REVISION LOG - ADOT Design Policy 1 Date of Original Issue: January 28, 2008
Development of Factored Bearing Resistance Chart by a Geotechnical Engineer for Use by a Bridge Engineer to Size Spread Footings on Soils Based on Service and Strength Limit States

Revision (Date)	**Changes made to current version of document**
1 (March 19, 2008)	1. Adjusted the settlement curves Figure 1 on Page 3 of 12 to reflect the effect of overburden stress at footing base level. 2. Changed assumed settlement in Step 1 of Section III.1 on Page 8 of 12 from δ_{st} = 0.75-in to 0.90-in to be consistent with changes in Figure 1.

Arizona Department of Transportation

Intermodal Transportation Division

206 South Seventeenth Avenue   Phoenix, Arizona 85007-3213

Janet Napolitano
Governor

Victor M. Mendez
Director

Sam Elters
State Engineer

February 25, 2008

To: Douglas Forstie, Highway Operations
Sam Maroufkhani, Highway Development
Floyd Roehrich, Valley Group
Larry Langer, Valley Project Management
Vincent Li, Statewide Project Management
Jean Nehme, Bridge Group
Mary Viparina, Roadway Group
John Carr, Engineering Technical Group
Vivien H. Lattibeaudiere, Engineering Consultants Section

From: John E. Lawson
Manager, Geotechnical Design Section
Materials Group (068R)

Subject: Geotechnical Design Policy
Load Resistance Factor Design (LRFD)
Development of Factored Bearing Resistance Chart by a Geotechnical Engineer for Use by a Bridge Engineer to Size Spread Footings on Soils based on Service and Strength Limit States

The AASHTO (2007) LRFD Bridge Design Specifications are mandatory for all federally funded bridge projects. This attached policy presents guidance for the design of spread footings using modified AASHTO (2007) criteria. The intent of this policy is to present a general overview of the development of the information needed by the bridge designer to design substructure elements consisting of spread footings.

Personnel, both within ADOT and design consultants working on projects that require LRFD for substructures, shall follow the attached policy. The designer should contact the ADOT Materials Group for an updated version of this policy in the event any interim revisions are made to AASHTO (2007), or a new edition of AASHTO is issued.

A factored bearing resistance chart shall be developed by the geotechnical engineer to permit the bridge designer to design a bridge substructure element consisting of a spread footing. The chart shall consist of factored net bearing resistance versus effective footing widths for various estimated settlements for service limit state. The chart shall also show maximum factored bearing resistance for the strength limit state. A modification of the AASHTO (2007) method for estimating settlements will be allowed and is included to more accurately determine settlements.

The procedures for development of the factored bearing resistance chart are given in the attached policy. If you have any questions regarding this bulletin, please contact John Lawson at 602-712-8130.

Arizona Department of Transportation

Materials Group - Geotechnical Design Section

MEMORANDUM

To: John Lawson, P.E., Manager, ADOT Geotechnical Design Section	**Date: January 28, 2008** **March 19, 2008 (Revision 1)**
From: Norman H. Wetz, P.E., Senior Geotechnical Engineer, James D. Wilson, P.E., Geotechnical Planning Engineer	**Subject: Development of Factored Bearing Resistance Chart by a Geotechnical Engineer for Use by a Bridge Engineer to Size Spread Footings on Soils Based on Service and Strength Limit States[1]**

Article 10.6.2.4.2 of AASHTO (2007) presents two methods for computing immediate settlement of footings. One method is based on elastic theory and the other method is based on an empirical method by Hough. Article C10.6.2.4.2 of AASHTO (2007) indicates that use of these methods will lead to "generally conservative settlement estimates." With respect to the Hough method, FHWA (2006)[2] noted that it over-predicts the settlement by a factor of 2 or more. The AASHTO method based on elastic theory gives similar results due to the unlimited depth of stress (or strain) influence below the footing. Such conservatism may lead to unnecessary use of costlier deep foundations or costly ground improvement measures for cases where spread footings may be viable. Therefore, ADOT will allow the use of the method presented in Section 8.5.1 of FHWA (2006) for computation of immediate settlement of a spread footing.

While this memorandum concentrates on immediate settlements, additional long-term (time-dependent) consolidation type settlements should also be evaluated by the geotechnical engineer, as appropriate, and reported to the bridge engineer, who can then evaluate whether total (immediate + long-term) settlements can be tolerated. The procedures in Article 10.6.2.4.3 of AASHTO (2007) shall be used for determination of long-term settlements.

---

1 This memorandum is based on AASHTO (2007). The designer should contact ADOT Materials Group for an updated version of this memorandum in the event any interim revisions to AASHTO (2007) are issued or a new edition of AASHTO is issued.

2 The full citation for FHWA (2006) is included in the References section and a free PDF copy is available from ADOT's Materials Group.

I. FHWA (2006) method

The method recommended in Section 8.5.1 of FHWA (2006) for computation of immediate settlements under spread footings is the method by Schmertmann, *et al.* (1978) modified to be consistent with the elastic (Young's) modulus values of various soils listed in Table C10.4.6.3-1 of AASHTO (2007). This modification was achieved through the use of a multiplier, "X", applied to the elastic modulus values listed in AASHTO (2007). Therefore, it is important that immediate settlement analyses be performed by using the version of Schmertmann's method as presented in Section 8.5.1 of FHWA (2006) rather than a method published in commonly available textbooks or other manuals. Interested designers may refer to Example 8-2 of FHWA (2006) for an illustrated step-by-step example documenting the use of the procedure for computation of immediate settlements.

II. Development of Factored Bearing Resistance Charts by Geotechnical Engineers

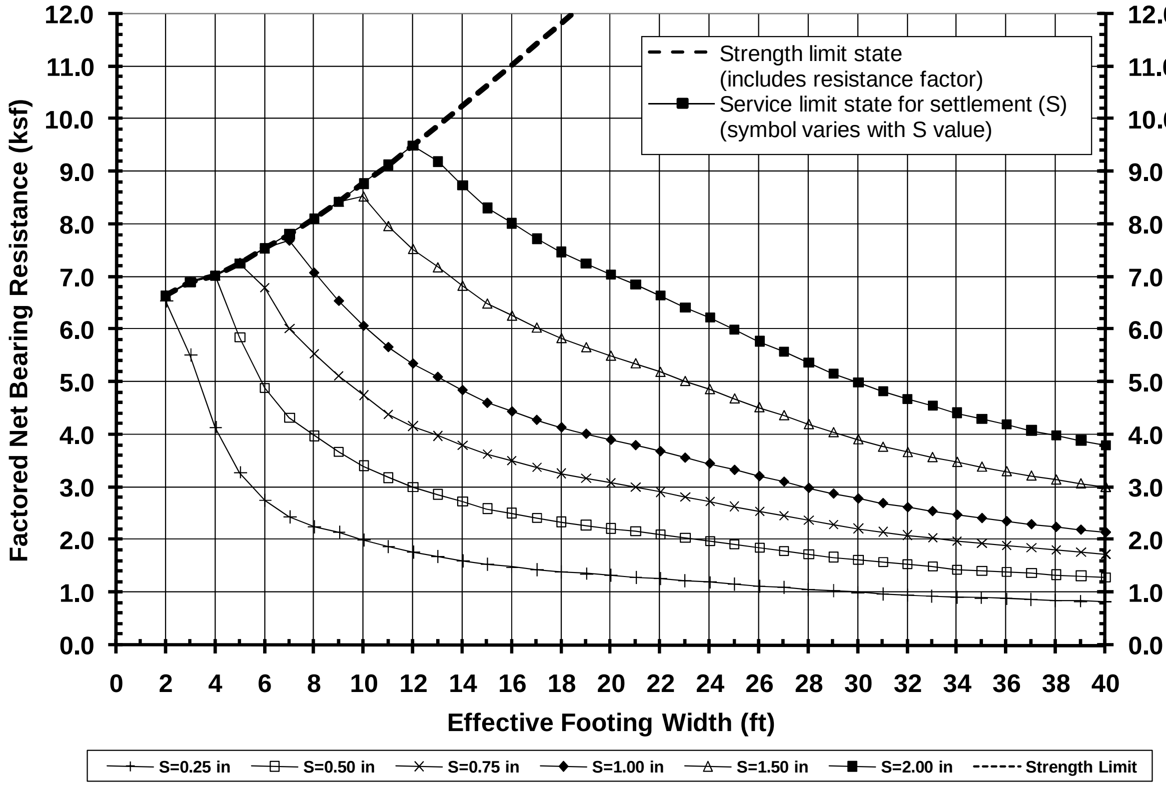
Recommendations regarding bearing resistance and settlements shall be provided in a chart termed "Factored Bearing Resistance Chart" wherein factored ***net*** bearing resistance is plotted on the ordinate versus ***effective*** footing width on the abscissa for a range of immediate settlements. Effective dimensions are defined later; they may or may not be the dimensions used for the structural design of the footing. A typical factored bearing resistance chart is shown in Figure 1 for the hypothetical soil profile and parameters shown in Table 1.

The steeply rising dashed curve presents the relationship between effective footing width and factored net bearing resistance corresponding to the strength limit state. The down-trending family of curves presents relationships between effective footing width and factored net bearing resistance for specific values of immediate settlement[3]. These curves are used to evaluate service limit states. Thus, the factored bearing resistance chart permits an evaluation of strength as well as service limit states.

The following should be noted with respect to Figure 1:

- The nominal ***net*** bearing resistance, q_{nn}, is evaluated for the final footing configuration by deducting from nominal bearing resistance, q_n, the overburden stress at the footing base elevation based on the final ground surface elevation above the footing. The nominal bearing resistance, q_n, can be determined by using appropriate equations in Article 10.6.3 of AASHTO (2007). The factored ***net*** bearing resistance, q_{Rn}, is obtained by multiplying the nominal net bearing resistance, q_{nn}, with an appropriate resistance factor, ϕ_b, from Table 10.5.5.2.2-1 of AASHTO (2007). Thus, $q_{Rn} = \phi_b\, q_{nn}$. The steeply rising dashed curve in Figure 1 shows the relationship between the factored net bearing resistance, q_{Rn}, and the effective footing width, B' and is used to evaluate the strength limit state. The effective footing width, B', accounts for load eccentricity as discussed later.

[3] The resistance factor for the service limit state in AASHTO (2007) is 1.0. Therefore, the nominal net bearing resistance at a given settlement value can also be thought of as a factored net bearing resistance at that value of settlement.



[4]Figure 1: Example of a Factored Bearing Resistance Chart for a footing of length, L′ = L = 150-ft (no eccentricity) and depth of embedment, D_f = 6-ft with base elevation of 994-ft. The resistance factor of ϕ_b= 0.45 is included in the strength limit state curve. "S" in the legend refers to immediate settlement.

- The service limit state refers to consideration of settlement under an applied vertical bearing stress, q_o, at the base of the loaded area. The limiting vertical bearing stress on a footing corresponding to a given settlement is obtained by inverting the settlement equation (Equation 8-16 in Section 8.5.1 of FHWA (2006)) to solve for bearing stress. By repeating the computation for a range of settlement values, the down-trending curves in Figure 1 can be generated (FHWA, 2006). The limiting vertical bearing stress determined in this manner represents the nominal bearing resistance of the soil corresponding to the settlement under consideration. This bearing stress corresponds to the equivalent ***net*** uniform[5] (Meyerhof) vertical bearing stress, q_{nveu}, at the base of the footing for the applicable limit state under consideration. Since the resistance factor for service limit state is 1.0, the factored net bearing resistance is equal to the nominal bearing resistance and the family of settlement-

[4] Figure 1 is specific to the hypothetical soil profile and parameters listed in Table 1. For a given project, use location-specific values of L′, D_f, footing base elevation, and ϕ_b in the figure caption.

[5] Uniform bearing stress distribution is used for sizing footings on soils based on geotechnical considerations as noted in Article 10.6.1.4 of AASHTO (2007). The net uniform bearing stress is determined by computing the net vertical loads at the base of the footing, i.e., after accounting for the depth of the footing. In other words, the net uniform bearing stress is defined as the total pressure at the base of the footing minus the overburden stress at the same level based on the final ground surface elevation above the footing (see Equation 3).

related curves can be plotted on the same chart as the factored net bearing resistance derived for the strength limit state based on shear considerations. This family of settlement-based curves is used to evaluate the service limit state.

Table 1
Hypothetical Soil Profile and Associated Soil Properties for Project-Specific Conditions

Depth (ft)	Soil Type	Total unit weight, γ_s, (pcf)	N_{60} (-)	Elastic Modulus, E_s, (tsf)
0 – 25	Fine to coarse Sands	120	25	$10N1_{60}$
25 – 75	Gravelly Sands	125	42	$12N1_{60}$
75 – 90	Fine to coarse Sands	120	18	$10N1_{60}$
90 – 130	Gravels	125	49	$12N1_{60}$

Notes:

1. Assume depth 0 to correspond to Elevation 1,000 ft.
2. N_{60} is energy-corrected Standard Penetration Test (SPT) N-value based on Eq. 10.4.6.2.4-2 of AASHTO (2007).
3. $N1_{60}$ is overburden-corrected N_{60}-value using the overburden correction factor as shown in Eq. 10.4.6.2.4-3 of AASHTO (2007).
4. Assume no groundwater was encountered.
5. Depth of 130-ft represents bottom of boring.
6. Due to the granular nature of soils, assume no long-term (creep type) settlements, i.e., assume $C_2 = 1$ as per Section 8.5.1.2 of FHWA (2006).
7. Elastic modulus is based on Table C10.4.6.3-1 of AASHTO (2007).
8. The length of the shear failure surface will be largely contained in the top layer extending to depth of 25-ft. Assume an effective friction angle, ϕ' of 30-degrees for this layer.
9. Since a SPT-based method is used, assume a resistance factor, ϕ_b, of 0.45 based on Table 10.5.5.2.2-1 of AASHTO (2007).
10. Assume that the ratio of the horizontal:vertical forces at the base of the footing is 0.12. This value is required for bearing resistance analysis based on consideration of shear failure (see Article 10.6.3.1.2 of AASHTO, 2007). Ask the bridge engineer for a typical value specific to the project.
11. Assume length of footing, L = 150-ft with no eccentricity in the L direction. Therefore $L' = L$. Length is usually based on the configuration of the bridge and the bridge engineer can provide this information.
12. Assume embedment depth of footing, D_f = 6-ft. Thus, footing base elevation = 994 ft and the total unit weight of soil within D_f is γ_s= 120 pcf.

- In Figure 1, the family of settlement-based curves was generated by using the FHWA (2006) method. For a proper representation of the overburden effects, the subsurface profile in Table 1 was divided into 5-ft layers. In actual designs, one can conceivably use an actual N_{60}-value at each SPT depth with the sampling interval, typically 5 feet, being equal to a layer of soil for analytical purposes. However, in this approach one has to be careful about critically reviewing anomalous SPT "refusal" values due to the effects of larger particle sizes such as gravel and boulders.

- For the factored net bearing resistance, q_{Rn}, on the Y-axis of a bearing resistance chart the equivalent ***net*** uniform (Meyerhof) vertical bearing stress, q_{nveu}, at the base of the footing should be used for the applicable limit state under consideration, e.g., strength limit state, service limit state, etc. The equivalent net uniform vertical bearing stress, q_{nveu}, is computed as follows

  Step 1: Compute the total (factored) equivalent uniform vertical bearing stress, q_{tveu}, as follows:

  $$q_{tveu} = V/A' \qquad \text{Eq. (1)}$$

  where V is the vertical component of the resultant of the total (factored) load for a given limit state at the base of the footing, including the effect of the weight of soil and footing above the footing base. As an approximation, the difference in unit weights of reinforced concrete and soil can be neglected within the thickness of the footing slab. The effective area of the footing, A', is determined as follows:

  $$A' = B'L' = (B - 2e_B)\,(L - 2e_L) \qquad \text{Eq. (2)}$$

  where e_B and e_L are the eccentricities in the B and L directions, respectively, see Article 10.6.1.3 of AASHTO (2007). Eccentricities shall be calculated based on total (factored) vertical loads and total (factored) moments at the base of the footing, i.e., including the effect of the weight of soil and footing above the footing base. As an approximation, the difference in unit weights of reinforced concrete and soil can be neglected within the thickness of the footing slab.

  Step 2: Compute the net equivalent uniform vertical bearing stress, q_{nveu}, as follows:

  $$q_{nveu} = q_{tveu} - \gamma_p\,(\gamma_s\, D_f) \qquad \text{Eq. (3)}$$

  where D_f is embedment depth of footing, γ_s is the unit weight of the soil within D_f, and γ_p is the load factor for permanent vertical earth pressure load (designated by the symbol "EV" in AASHTO (2007)) consistent with the limit state used to determine V, e_B and e_L. The load factor for "EV" load can be obtained from Tables 3.4.1-1 and 3.4.1-2 of AASHTO (2007).

- The effective footing width on the X-axis of a bearing resistance chart represents the least lateral ***<u>effective</u>*** dimension of the footing. Thus, once B' and L' are computed as part of Equation (2), the smaller of the two effective dimensions is the effective footing width.

- The FHWA (2006) method defines a footing as continuous (or strip) when L/B (or L'/B') ≥ 10. Footings with 1 < L/B (or L'/B') <10 are categorized as rectangular and those with L/B (or L'/B') = 1 are categorized as square or circular. In order for the factored bearing resistance chart to be based on consistent definitions, the definition of the shape of the footing for the determination of the bearing resistance based on shear considerations for the strength limit state should be the same as that for the settlement method, i.e., the FHWA (2006) method.

- The footing size determined from the chart is a function of the depth of embedment of the footing, D_f, and the effective length of the footing, L′. The depth of embedment, D_f, is the vertical distance between the elevation of the lowest finished permanent grade above the footing and the elevation of the base of the footing. Each factored bearing resistance chart is developed for a given footing effective length, L′, and a minimum depth of embedment, D_f. Therefore, these quantities in addition to the footing base elevation and the resistance factor must be clearly labeled on the chart or noted in the caption as shown in Figure 1. If the actual dimensions of D_f and/or L′ vary by more than ±20% from those noted on the charts then a new chart should be developed for the actual values of D_f and L′.

- Each factored bearing resistance chart should be specific to a given foundation element and should be developed based on location-specific geotechnical data. Consequently the charts should not be used for foundations at locations other than those at which they are applicable.

III Use of Factored Bearing Resistance Charts by Bridge Engineers

The factored bearing resistance chart presented in Figure 1 provides the bridge engineer with a powerful tool for studying the interrelationships among effective footing widths, uniform bearing pressures (or resistances) and settlements. A common step-by-step procedure to size a spread footing is described in Section III.1. For the sake of discussion, assume the terminology listed in Table 2. Table 3 provides values of the various parameters that will be used to illustrate the step-by-step procedure.

Table 2
Terminology for Parameters Used in Sizing a Spread Footing

Parameter	**Limit State***	
	Service I Limit State	**Strength I (maximum)**
Vertical component of the resultant load	V_{SER}	V_{STR}
Moment	M_{SER}	M_{STR}
Eccentricity	$e_{B\text{-}SER}$ ($=M_{SER}$ / V_{SER})	$e_{B\text{-}STR}$($=M_{STR}$ / V_{STR})
Equivalent total uniform bearing stress (based on Equation 1)	$q_{tveu\text{-}SER}$	$q_{tveu\text{-}STR}$
Equivalent net uniform bearing stress (based on Equation 3)	$q_{nveu\text{-}SER} = q_{tveu\text{-}SER} - \gamma_p (\gamma_s D_f)$	$q_{nveu\text{-}STR} = q_{tveu\text{-}STR} - \gamma_p (\gamma_s D_f)$
* Only one strength limit state is used herein for illustration purposes. In actual design all applicable strength limit states must be considered.		

Table 3
Example Parameters for an Abutment Footing (L=150-ft)

Parameter	**Limit State***	
	Service I Limit State	**Strength I (maximum)**
Vertical component of the resultant load	V_{SER} = 9,080 kips	V_{STR} = 12,028 kips
Moment	M_{SER} = 22,720 k-ft	M_{STR} = 35,290 k-ft
Eccentricity in the B-direction**	$e_{B\text{-}SER}$ = 2.50-ft	$e_{B\text{-}STR}$ = 2.93-ft
* Only one strength limit state is used herein for illustration purposes. In actual design all applicable strength limit states must be considered. ** The B-direction is the direction of the least lateral dimension of the footing. The eccentricity in the length (L) direction for an abutment footing is commonly negligible and is assumed to be zero for this example case, i.e., L′ = L. For cases where the footing has eccentricity in both directions, the eccentricity in the length (L) direction should also be evaluated. In the case of the eccentricity in both directions, the least lateral dimension is the smaller dimension of the footing after adjustment for the eccentricities.		

III.1 Step-by-Step Procedure for Sizing a Spread Footing at Service and Strength Limit States

1. Assume a total footing width, B_{SER}. Calculate effective footing width $B'_{SER} = B_{SER} - 2e_{B\text{-}SER}$. Calculate $q_{nveu\text{-}SER}$. Enter the chart with $q_{nveu\text{-}SER}$ and effective footing width, B'_{SER} and determine the settlement, δ_s. Compare δ_s with for a target tolerable total settlement value, δ_{st}. If necessary iterate the footing width until $\delta_s \approx \delta_{st}$.

   Example: Assume $\delta_{st} = 0.90$-in.[6] Assume B_{SER} = 15-ft
   Since $e_{B\text{-}SER}$ = 2.50-ft, $B'_{SER} = B_{SER} - 2e_{B\text{-}SER}$ = 15-ft – 2(2.5-ft) = 10-ft
   For L′ = 150-ft and B'_{SER} = 10-ft, A'_{SER} = (150-ft) (10-ft) = 1,500 ft^2
   $q_{tveu\text{-}SER} = V_{SER}/A'_{SER}$ = 9,080 kips / 1,500 ft^2 = 6.05 ksf

   From Table 3.4.1-1 of AASHTO (2007) the load factor γ_p for vertical earth pressure corresponding to Service I limit state is 1.0. Using the values provided in Note 12 of Table 1, the factored overburden stress at footing base level = $\gamma_p(\gamma_s D_f)$ = (1.0)(0.120 kcf) (6-ft) = 0.72 ksf

   $q_{nveu\text{-}SER} = q_{tveu\text{-}SER} - \gamma_p(\gamma_s D_f)$ = 6.05 ksf – 0.72 ksf = 5.33 ksf

   Enter Figure 1 with B'_{SER} = 10-ft from X-axis and $q_{veu\text{-}SER}$= 5.33 ksf from the Y-axis and find the point of intersection on the chart which represents the estimated settlement for this particular set of B'_{SER} and $q_{veu\text{-}SER}$ values. From Figure 1, the estimated settlement, δ_s, is slightly less than 0.90-in. Since $\delta_s \approx \delta_{st}$ the assumed footing width is correct. Otherwise, repeat the process with another assumed footing width till $\delta_s \approx \delta_{st}$ is achieved.

2. Check if $e_{B\text{-}STR} < B_{SER}/4$. If yes, then denote the total footing width after this step as B_{STR} since it is based on comparison with strength limit state criterion for eccentricity.

   Example: For B_{SER} = 15-ft, $B_{SER}/4$ = 3.75-ft
   From Table 3, $e_{B\text{-}STR}$ = 2.93-ft.
   Since $e_{B\text{-}STR} < B_{SER}/4$, a footing width of 15-ft is acceptable based on eccentricity consideration.
   Denote the footing width for strength limit state design as B_{STR} = 15-ft. This is the footing width that is also used for structural design and detailing.

3. For strength limit state, determine the effective width of the footing $B'_{STR} = B_{STR} - 2e_{B\text{-}STR}$ and $q_{nveu\text{-}STR}$

   Example: For B_{STR} = 15-ft and $e_{B\text{-}STR}$ = 2.93-ft.
   $B'_{STR} = B_{STR} - 2e_{B\text{-}STR}$ = 15-ft – 2(2.93-ft) = 9.14-ft.
   For L′ = 150-ft and B'_{STR} = 9.14-ft, A'_{STR} = (150-ft) (9.14-ft) = 1,371 ft^2

[6] The value of 0.90-in is used for illustration purposes and does not represent a standard or fixed value. In actual design, the value shall be based on the tolerable total settlement determined by the bridge engineer.

$q_{tveu\text{-}STR} = V_{STR}/A'_{STR} = 12{,}028$ kips / $1{,}371$ ft^2 = 8.77 ksf

From Table 3.4.1-2 of AASHTO (2007), the load factor γ_p for permanent vertical earth pressure corresponding to Strength I (maximum) limit state is 1.35 for "Retaining Walls and Abutments." Using the values provided in Note 12 of Table 1, the factored overburden stress at footing base level = $\gamma_p(\gamma_s D_f)$ = (1.30)(0.120 kcf) (6-ft) ≈ 0.97 ksf

$q_{nveu\text{-}STR} = q_{tveu\text{-}STR} - \gamma_p(\gamma_s D_f)$ = 8.77 ksf – 0.97 ksf = 7.80 ksf

4. For B'_{STR} determine the factored net bearing resistance, q_{Rn}, from the steeply rising curve based on shear strength considerations.

   Example: Enter Figure 1 with B'_{STR} = 9.14-ft from X-axis and find the point of intersection with the steeply rising curve above the settlement curves. This point of intersection represents the factored net bearing resistance, q_{Rn}, for $B'_{STR.}$ From Figure 1, for B'_{STR} = 9.14-ft, $q_{Rn} \approx 8.4$ ksf.

5. If $q_{Rn} > q_{nveu\text{-}STR}$ then footing width B_{STR} is adequate.

   Example: From Step 3, $q_{nveu\text{-}STR}$ = 7.80 ksf
   From Step 4, $q_{Rn} \approx 8.4$ ksf
   Since $q_{Rn} > q_{nveu\text{-}STR}$, the footing width B_{STR} is adequate.

Repeat the above steps for all applicable strength and service limit states and determine the governing spread footing size, i.e., total width (B) and total length (L). For every limit state, the spread footing size should also be checked for sliding as per the requirements of Article 10.6.3.4 of AASHTO (2007).

There are several other ways to use factored bearing resistance charts. For example, one can conceivably establish a preferred footing size based on project space constraints and then enter the chart from the X-axis to design the footing. Alternatively, one can select a tolerable settlement contour curve and evaluate several alternative combinations of factored bearing resistance and effective footing width in an attempt to balance the settlements across several discrete footings at a given substructure element.

Regardless of the way the data in a factored bearing resistance chart are evaluated, the bridge engineer can perform parametric analyses to optimize the size of footings. It is anticipated that some level of iterative analysis will be required to determine a footing configuration that meets the requirements of the various limit states. Commonly, the service limit state is evaluated first to establish the size of the footing and then the footing is checked with respect to the strength limit state.

Finally, it should be remembered that the structural design of the footing should be performed by using the total governing footing width (B) and length (L) with the appropriate bearing stress distribution as per Article 10.6.5 of AASHTO (2007) - uniform if no eccentricity, trapezoidal or triangular if there is eccentricity.

III.2 Evaluation of Extreme Event Limit State

Extreme Event Limit State defines criteria for extreme events such as earthquakes, and hurricanes. An extreme event limit state is evaluated at a nominal resistance based on shear considerations. From the factored bearing resistance chart, the nominal resistance values may be derived by dividing the factored bearing resistance values of the steeply rising dashed curve by the value of the resistance factor, ϕ_b, listed in the figure caption. Extreme event limit states often involve other considerations that may affect the selection of spread footings. Such conditions are external to the use of the bearing resistance chart and must be carefully evaluated separately.

IV. Reliability of Settlement Estimates and Estimating Differential Settlements

All analytical methods used for estimating settlements are based on certain assumptions. Therefore, there is an inherent uncertainty associated with the estimated values of settlements regardless of the method used to make the estimate. The uncertainty of the estimated differential settlement between two support elements is larger than the uncertainty of the estimated absolute settlements at the two support elements used to calculate the differential settlement, e.g., between abutment and pier, or between piers. For example, if one support element actually settles less than the amount estimated while the other support element actually settles the amount estimated, the actual differential settlement will be larger than the difference between the two values of estimated settlement at the support elements. Based on guidance provided in Section 8.9 of FHWA (2006), the following approach is recommended for the evaluation of differential settlements between adjacent support elements:

- The actual settlement at any support element could be as large as the calculated value of the settlement.

- At the same time, the actual settlement of the adjacent support element could be zero.

Use of the above approach would result in an estimated maximum possible differential settlement equal to the larger of the two total settlements calculated at either end of any span. The angular distortions generated by differential settlements can be evaluated by using the guidance in Article C10.5.2.2 of AASHTO (2007).

V. Staged Construction Analysis

The factored bearing resistance chart can be used by the bridge engineer to perform a staged-construction type of analysis. To achieve this type of analysis for a footing having a given effective width as referenced to the X-axis, the bridge engineer can enter the chart with various bearing pressures from the Y-axis (i.e., factored net bearing resistance axis) corresponding to specific construction points and interpolate the associated values of settlement from the family of curves that defines the service limit state. Common construction points are as follows:

- End-of-construction of spread footing
- End-of-construction of pier or abutment, but before placement of superstructure
- After placement of superstructure
- After application of live load

Evaluation of incremental displacements between various construction points when taken in conjunction with guidance on angular distortions provided in Article C10.5.2.2 of AASHTO (2007) can permit a more efficient design of the substructure as well as the superstructure. For example, settlements that occur before the placement of the superstructure can generally be compensated for by adjusting the bearing levels. Therefore, such settlements may be irrelevant with respect to their effect on the design of the superstructure itself. Properly accounting for such settlements will lead to smaller settlements for the construction stages that follow, which may be of more interest from the viewpoint of differential settlement, e.g., between end-of-construction of a pier and after placement of the superstructure. Such considerations may lead to more efficient designs for both the substructure and the superstructure.

VI. Closing Comments

This memorandum contains guidance for the method to be used for determining immediate settlements under a spread footing. The bearing resistance chart is recommended as the preferred format for presenting geotechnical recommendations for design. Also presented in this memorandum are suggestions on how to use the bearing resistance chart. Additional guidance is provided on estimating differential settlement.

In addition, the geotechnical engineer should provide the bridge engineer with guidance to evaluate differential settlements between adjacent support elements. Based on site- and project-specific conditions the geotechnical engineer could modify the guidance provided in Section IV of this memorandum as appropriate. If such guidance is not included in the geotechnical report, the bridge engineer should request the information from the geotechnical engineer.

VII. References

AASHTO (2007). ***AASHTO LRFD Bridge Design Specifications***. 4th Edition. American Association of State Highway and Transportation Officials, Washington, D.C.

FHWA (2006). ***Soils and Foundations – Volumes I and II***. Authors: Samtani, N. C. and Nowatzki, E. A., Publications No. FHWA NHI-06-088 and FHWA NHI-06-089, Federal Highway Administration, Washington, D.C.

Schmertmann, J. H., Hartman, J. P., and Brown, P. R. (1978). "Improved Strain Influence Factor Diagrams." American Society of Civil Engineers, ***Journal of the Geotechnical Engineering Division***, 104 (No. GT8), 1131-1135.